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The Dark Side of the Universe

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Abstract

I will begin by reviewing the evidence for Dark Matter in the Universe, as well as the candidates for dark matter. At most 20% of the dark matter in galaxies can be in the form of MACHOs (Massive Compact Halo Objects); the remainder appears to be some unknown exotic component. The most sensible candidates from the point of view of particle physics are axions and WIMPs (Weakly Interacting Massive Particles), where WIMPs may be supersymmetric particles. Three recent claims of possible detection of WIMP dark matter are tantalizing and will be discussed: the DAMA annual modulation, the HEAT positron excess, and gamma-rays from the Galactic Center. In addition, I will discuss the dependence of signals in detectors on the mass distribution in the Galactic Halo. In particular, the Sagittarius stream can be a smoking gun for WIMP detection.

Key words:
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1. The Dark Matter Problem

The universe consists of 4% ordinary atoms (baryonic matter) $\sim 26\%$ Dark Matter, and $\sim 70\%$ Dark Energy. Measurements of the Cosmic Microwave Background Radiation (CMBR) have determined the total mass density and the geometry of the universe [1]. The fact that ordinary atoms are 4% is inferred from element abundances in Big Bang Nucleosynthesis as well as from the CMBR. The 'best' matter density has been determined by WMAP [1] to be $\Omega_m h^2 = 0.135(+0.008, -0.009)$ where the best fit value of the Hubble constant is $h = 0.7$. The components are $\Omega_\nu h^2 < 0.0076$ (95% C.L.), $\Omega_b h^2 = 0.0224 \pm 0.0009$, and $\Omega_{DM} h^2 = 0.113(+0.008, -0.009)$ in units of 1.879×10^{-29} g/cm^3 where subscript DM refers to dark matter.

Evidence for the 70% dark energy in the universe comes from observations of distant supernovae [2]: the supernovae are dimmer than expected, as is most easily explained by an accelerating universe. There are two different approaches to the dark energy: (i) a vacuum energy such as a cosmological constant or time-dependent vacuum may be responsible [3], or (ii) it is possible that General Relativity is incomplete and that Einstein's equations need to be modified [4]. Note, however, that this dark energy does not resolve or contribute to the question of dark matter in galaxies, which remains as puzzling (if not more) than twenty years ago.

95% of the mass in galaxies and clusters of galaxies is made of an unknown dark matter component. This fact is known from (i) rotation curves, (ii) gravitational lensing, and (iii) hot gas in clusters. The speeds of objects in orbit around the centers of galaxies are determined by the mass interior to

the radius of the orbit. Contrary to what would be expected from the luminous mass in galaxies, these rotation curves are flat to very large radii, as can only be explained if there is an order of magnitude more dark than luminous matter. Lensing provides another way to detect dark matter: it makes light bend. Telescopes monitor the light from distant objects such as galaxies or quasars: the amount of intervening mass determines how much this light is bent. Lensing effects can be responsible for multiple images of the source object, can cause the source to appear brighter (microlensing), or can distort the shape of the source (e.g. shear). Recent data from the SLOAN Digital Sky Survey, e.g., have found that our Milky Way Galaxy is five times more massive than previously thought and extends out to almost a Mpc in radius [5].

Another piece of evidence for dark matter comes from the hot gas in clusters. X-ray images of the Coma Cluster, a rich cluster of galaxies, taken by the ROSAT satellite [6] demonstrate that COMA has a large amount of hot gas. Without a significant dark matter component in the cluster to provide a gravitational potential well, the hot gas would evaporate and we wouldn't see it. The majority of the mass in galaxies and clusters clearly consists of a dark matter component.

2. Dark Matter Candidates

There is a plethora of dark matter candidates. The most simple are MACHOs, or Massive Compact Halo Objects, as these would be made of ordinary matter in the form of fainst stars or stellar remnants. However, there are not enough of these to completely resolve the question. Of the nonbaryonic candidates, the most popular are the WIMPS (Weakly Interacting Massive Particles) and the axions, as these particles have been proposed for other reasons in particle physics. Ordinary massive neutrinos are too light to be cosmologically significant, though sterile neutrinos remain a possibility. Other candidates include primordial black holes, nonthermal WIMPzillas, and Kaluza-Klein particles which arise in higher dimensional theories.

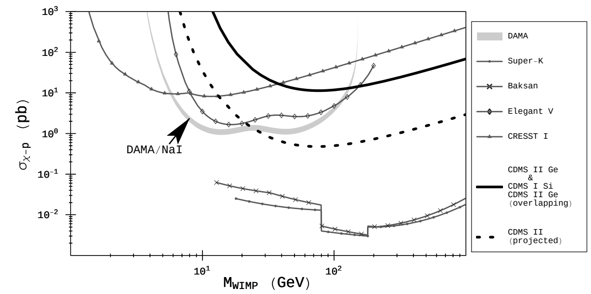

Fig. 1. WIMP-proton cross-section limits for the case $a_n = 0$. Super-K and Baksan rule out the DAMA results over their analysis ranges and CRESST I limits DAMA at low masses, but WIMPs between 6-13 GeV are consistent with all results for this case.

2.1. *MACHOs*

MACHO candidates include faint stars, planetary objects (brown dwarfs), and stellar remnants (white dwarfs, neutron stars, and black holes). Microlensing experiments (the MACHO [7] and EROS [8] experiments) as well as a combination of other observational (HST) and theoretical results [9] have shown that MACHOs less massive than 0.1 solar masses are insignificant in the Galaxy. However, there is a detection [7] of a roughly 20% halo fraction made of $\sim 0.5 M_\odot$ objects which might be made of stellar remnants such as white dwarfs. We found a number of constraints: the progenitors produce observable element abundances (C,N,He), they require an enormous mass budget, the initial mass function must be extremely sharply peaked, and, most important, the progenitors produce observable infrared radiation. Our conclusion from these constraints is that at most 20% of the Galactic Halo can be made of stellar remnants [10].

An interesting recent development [11] is a candidate MACHO microlensing event that has been found in M87, a giant elliptical galaxy in the VIRGO cluster that is 14 Mpc away. This candidate, which must be confirmed in future HST observations with more statistics, is consistent with the results of the MACHO data discussed above.

2.2. *Axions*

The good news is that cosmologists don't need to "invent" new particles. Two candidates already exist in particle physics for other reasons: axions and WIMPs. Axions with masses in the range $10^{-(3-6)}$ eV arise in the Peccei-Quinn solution to the strong-CP problem in the theory of strong interactions. Axion bounds [12] from the ADMX cavity experiment are approaching the remaining parameter range. I wanted also to mention an idea we recently proposed for inflation with the QCD axion [13]. In chain inflation, the potential looks like a tilted cosine, and the universe tunnels from higher to lower minima in stages, with a fraction of an efold at each stage, adding to sufficient inflation.

3. WIMPs (Weakly Interacting Particles)

WIMPs are also natural dark matter candidates from particle phyiscs. The relic density of these particles comes out to be the right value: $\Omega_\chi h^2 = (3 \times 10^{-26}\mathrm{cm}^3/\mathrm{sec})/\sigma_{ann}$, where the annihilation cross section σ_{ann} of weak interaction strength automatically gives the right answer. The best WIMP candidate is motivated by Supersymmetry (SUSY): the lightest neutralino in the Minimal Supersymmetric Standard Model. Supersymmetry in particle theory is designed to keep particle masses at the right value. As a consequence, each particle we know has a partner: the photino is the partner of the photon, the squark is the quark's partner, and the selectron is the partner of the electron. The lightest superysmmetric partner is a good dark matter candidate (see the reviews by [14]).

There are four ways to search for dark WIMPs. In direct detection experiments, the WIMP scatters off of a nucleus in the detector, and a number of experimental signatures of the interaction can be detected [15,16]. In indirect detection experiments, neutrinos are detected from the Sun or Earth that arise as annihilation products of captured WIMPs; the first papers suggesting this idea were [17] in the Sun and [18] in the Earth. A third way to detect WIMPs is to look for anomalous cosmic rays from the Galactic Halo: WIMPs in the Halo can annihilate with one another to give rise to antiprotons, positrons, or neutrinos [19]. Fourth, neutrinos, Gamma-rays, and radio waves may be detected as WIMP annihilation products from the Galactic Center [20].

In direct detection experiments, the event rate (number of events/(kg of detector)/(keV of recoil energy) is

$$dR/dE = \frac{\rho\sigma_0 F^2(q)}{2m\mu^2} \int\limits_{v>\sqrt{ME/2\mu^2}} \frac{f(v,t)}{v} d^3v \qquad (1)$$

$f(v,t)$ is the WIMP velocity distribution, μ is the reduced mass of the WIMP/nucleus system, $F(q)$ is the nuclear form factor, and the cross section is

$$\sigma_0 = \frac{A^2\mu^2}{\mu_p^2}\sigma_p \quad \mathrm{spin-independent}; \qquad (2)$$

$$\sigma_0 = \frac{4\mu^2}{\pi}|\langle S_p\rangle G_p + \langle S_n\rangle G_n|^2 \quad \mathrm{spin-dependent} (3)$$

where the spin-independent cross section scales as atomic number squared (A^2) and the spin-dependent cross section depends on the spin content of the nucleon.

Three Claims of possible WIMP dark matter detection: In the past few years there have been three claims of possible WIMP dark matter detection: (1) the DAMA annual modulation, (2) the HEAT postiron excess, and (3) Gamma-rays from the Galactic Center.

(1) DAMA: In 1986, I was part of a collaboration [16] that suggested using the annual modulation of a WIMP signal to differentiate it from background (see also [21]). Because the Sun orbits around the Galactic Center, we are moving into a wind of WIMPs. Since the Earth also travels around the Sun, the relative velocity varies with the time of year, giving rise to a modulation in the count rate. The DAMA experiment [22] has seven years of data with exactly this type of annual modulation at the 6σ level. However, a WIMP interpretation is controversial. In fact, a spin-independent cross section with canonical Maxwellian halo is excluded by the null results of the CDMS-II experiment [23] (but see also [24]). We asked whether WIMPs with spin-dependent cross sections explain both the positive DAMA results as well as the

null results from other experiments [25]. While we found that neutron-only interactions are ruled out, proton-only or mixed interactions can still survive as explanations of DAMA data for WIMP masses in the 6-13 GeV range. The most stringent bounds arise from SuperKamiokande. We note that if the WIMPs are not neutralinos, and are not their only antiparticles, then the SuperK results do not apply and the WIMP mass could still be as large as 100 GeV and be in agreement with DAMA and all other existing data. Figure 1 illustrates our results.

(2) Gamma rays: WIMP annihilation at the Galactic Center? Recently there have been claims from both the CANGAROO [26] and HESS [27] experiments of detections of Gamma Rays from the Galactic Center, each with a very different energy spectrum. One can fit the CANGAROO data with a 2 TeV WIMP, and the HESS data with a 20 TeV WIMP [28]. However, it is not easy to get this intensity in SUSY models, and it may be easier to explain the data with an astrophysical origin rather than a SUSY detection. Also, Finkbeiner [29] suggested that excess microwave emission observed by WMAP in the inner Galaxy (inner $\sim 1 - 2$kpc) may be interpreted as dark matter annihilation in the inner galaxy. Currently alternative astrophysical explanations exist for the photons from the Galactic Center.

In the future, a signal more compelling than the gamma-ray continuum would be a gamma-ray line, which is characteristic of WIMP annihilation [30]. GLAST may observe such a line below 80 GeV.

(3) Positron excess: The HEAT balloon, using two entirely different instruments, found an anomaly in the cosmic ray positron flux [31]. One possible explanation is dark matter annihilation, as studied by [32]; a boost factor of at least 30 would be required for a thermal SUSY explanation. A second possible explanation is that we do not understand cosmic ray propagation.

There have been three recent claims of possible WIMP detection: DAMA annual modulation, Gamma-rays from the Galactic Center, and the HEAT positron excess. All three of these signals are very tantalizing hints of dark matter detection, but all three may have more conventional explanations. Currently the identity of the dark matter remains an enigma.

4. Shape of Galactic Halo

The dark matter distribution in the Halo of the Galaxy affects the signal in detectors, as seen in Eq.(1). Numerical simulations indicate that galaxies formed by mergers of smaller objects. Recently, one such stream has been found: the Sagittarius stream. On the other side of the Galactic Center is a small dwarf galaxy, Sagittarius, which is being shredded up by our Milky Way: this is a merger in progress. Two tidal streams of stars are seen coming off of the Sagittarius Galaxy. One of them is seen to pass near the Solar System. These streams are likely to contain dark matter, in an abundance that adds an amount (1-20)% of the local halo density. We calculated the effect of this dark matter stream in detectors [33]. This contribution enhances the count rate in dark matter detectors, but only up to a cutoff in energy in the energy recoil spectrum. We found that the location of the cutoff changes with the time of year, so that there is an annual modulation both of the rate and of the endpoint energy as shown in Figure 3. The stream also shifts the peak date of the annual modulation of the signal from June 2 to another date, depending on the stream density. With a directional detector such as DRIFT-II [34], the stream would stick out like a sore thumb. In sum, the Sagittarius stream increases the count rate in detectors up a cutoff in the energy spectrum, the cutoff location moves in time, the stream sticks out like a sore thumb in directional detectors, it changes the date of the peak in the annual modulatoin, and the stream provides a smoking gun for WIMP detection.

5. Conclusion

I have discussed the evidence for dark matter in the universe: rotation curves, lensing, hot gas in clusters, and the cosmic microwave background radiation. Future goals would be to find both the baryonic and non-baryonic contributions to dark matter. MACHOs can provide at most 20% of the dark matter in galaxies. The remainder appears to be some form of exotica. The most sensible candidates from the point of view of particle physics

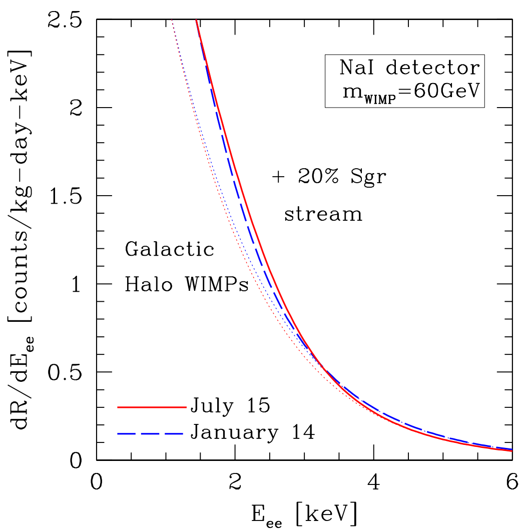

Fig. 2. Count rate of 60 GeV WIMPs vs. recoil energy. The dotted lines show the count rate from Galactic (isothermal) halo WIMPs alone. The solid and dashed lines show the step in the count rate (in July and January) if we include the Sgr stream WIMPS. In this plot, the stream contributes an additional 20% to the local Halo density.

are axions and WIMPs, where WIMPs may be supersymmetric particles. Recently there have been three claims of possible WIMP detections, and the theoretical implications of each was discussed. These three claims are currently tantalizing but not confirmed. The expectations for signals in detectors depend on Halo models, and I showed the implications of the Sagittarius stream in detectors.

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